The Spectroscopic Foundation of Radiative Forcing by Carbon Dioxide

Marty Mlynczak

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Team Members

- Marty Mlynczak - LaRC
- Taumi Daniels – LaRC
- Dave Kratz - LaRC
- Jeff Mast - SSAI
- Linda Hunt - SSAI
- Dan Feldman – Berkeley Lab
- Bill Collins – Berkeley Lab
- David Fahey – NOAA ESRL
- Eli Mlawer – AER
- Matt Alvarado – AER
- L. W. Anderson – U. Wisconsin Physics
- Jim Lawler – U. Wisconsin Physics

Background

- Princeton physics professor W. Happer has been making the case that climate forcing by CO_2 is greatly overestimated
- His argument is that climate models use the classic Voigt lineshape for CO_2 radiative transfer
- He further argues that models take the line wings out "to infinity" from line center
- However, the CO_2 wings are in fact sub-Lorentzian, and he argues that improper use of the Voigt shape is the reason climate models overestimate global warming, and this is why global warming is not what it is predicted to be (e.g., the hiatus)

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Why has global warming paused?*

William Happer
Department of Physics, Princeton University, Princeton, NJ 08544, USA
happer@princeton.edu

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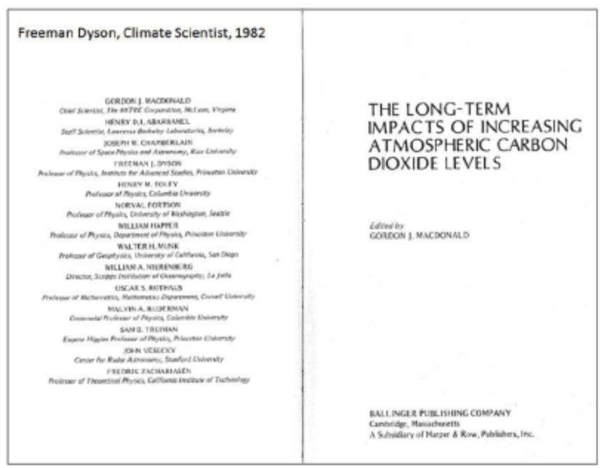
1. Introduction

Freeman Dyson has been interested in climate for most of his life. He coauthored one of the earliest books on the interplay of CO_2 and climate in 1982:

> "The Long-term Impacts of Increasing Atmospheric Carbon Dioxide Levels", edited by Gordon J. MacDonald (Ballinger Publishing Company, 2008).



Slide 1.

*Based on a talk given at the conference *Dreams of Earth and Sky: A Celebration for Freeman Dyson*, Institute for Advanced Study, Princeton, 27 September 2013

Background (2)

- The sub-Lorentzian nature of CO_2 line wings has been known for over 50 years
- S. Roland Drayson (1966) in his pioneering paper on the line-by-line radiative transfer calculation noted the need to account for sub-Lorentzian wings in CO_2
- Kunde and Maguire (1974) used sub Lorentzian wings in RT calculations in planetary atmospheres
- Fels and Schwarzkopf (1981) noted sub-Lorentzian wing effects in early climate modeling work
- So the physics has not been overlooked or unknown
- Niro et al (1990's), including Ken Jucks as co-author, have developed state-of-science algorithms to apply line mixing and sub-Lorentzian wings in CO2 in the IR
- These are used in LBLRTM (and hence, RRTM, in climate models)

Atmospheric Transmission in the CO_2 Bands Between 12 μ and 18 μ

S. Roland Drayson

Calculations have been made of high-resolution transmission in the CO_2 absorption bands between 12 μ and 18 μ by direct integration across the bands, for both homogeneous and atmospheric slant paths. Mixed Doppler-Lorentz broadening has been used at pressures lower than 100 mb. A method to eliminate the Curtis-Godson approximation has been developed and applied to the slant-path calculations. Comparisons have been made with previous theoretical and experimental data, and reasons for the discrepancies are discussed.

Roland Drayson's paper pioneering the line-by-line method of radiative transfer calculation

Introduction

In recent years there has been a growing interest in atmospheric infrared radiative transfer, with applications to the earth and other planets. On the earth, these applications include the investigation of radiative heating and cooling, and the interpretation of satellite radiometer measurements, while the composition, surface pressure, temperature, etc., of planetary atmospheres may be inferred from suitable remote radiometric observations. Broad-band radiometers are being supplemented and replaced by instruments of much higher spectral resolution and photometric accuracy, leading to increased demands on the accuracy of calculations.

One of the chief problems in the interpretation of data stems from the difficulty in calculating atmospheric transmission functions due to molecular band absorption. These functions are generally obtained in one of two ways.

(a) From laboratory absorption cell measurements. They are subject to experimental errors, which, in the case of low concentrations of the absorbing gas, may be severe. Considerable extrapolation over temperature, pressure, and path length is required before application to nonhomogeneous atmospheric slant paths can be made.

(b) By theoretical calculations using band models. These are generally unsatisfactory, for reasons discussed in detail in a later section. They cannot readily be applied to certain sections of the absorption bands, which are of extreme importance in the upper atmosphere.

An alternate procedure is direct integration with respect to frequency across the absorption band, a procedure that has become increasingly attractive with the advent of modern digital computing techniques. The first serious attempt to use the method was in 1961 by Hitschfeld and Houghton,[1] who integrated over a small portion of the 9.6-μ ozone band. More recently, Gates *et al.*[2,3] used the same technique for the 1.8-μ water vapor band, and Shaw and Houghton[4] for the 4.7-μ CO band. The same general approach has been used in the calculations described in this paper, but it has been extended to include atmospheric slant paths.

Homogeneous Paths

Line Shapes

Before atmospheric absorption calculations are performed, it is extremely important to decide on the appropriate line shape. The theory governing the shapes and half-widths is difficult to apply; furthermore, experimental work is hampered by such factors as the overlapping of lines, the difficulty in obtaining suitable high-resolution instruments, and the effect of instrument aperture functions on the spectra. However, there is good evidence[5] to support the use of the Lorentz line shape where pressure-broadening is the dominant feature and the mixed Doppler-Lorentz line shape at lower pressures.

The Lorentz Line Shape

This shape has a very simple form and has the great advantage that it is easy to deal with analytically. The absorption coefficient at frequency ν, for a single line strength S, centered at frequency ν_0, is given by

$$k_\nu = \frac{S}{\pi}\frac{\alpha_L}{(\nu-\nu_0)^2+\alpha_L^2}, \qquad (1)$$

where α_L is the Lorentz half-width (i.e., half the total line-width at half-intensity) at temperature T and pressure p. The dependence of α_L upon these parameters is given by

The author is with the High Altitude Engineering Laboratory, Department of Aerospace Engineering, The University of Michigan, Ann Arbor, Michigan.

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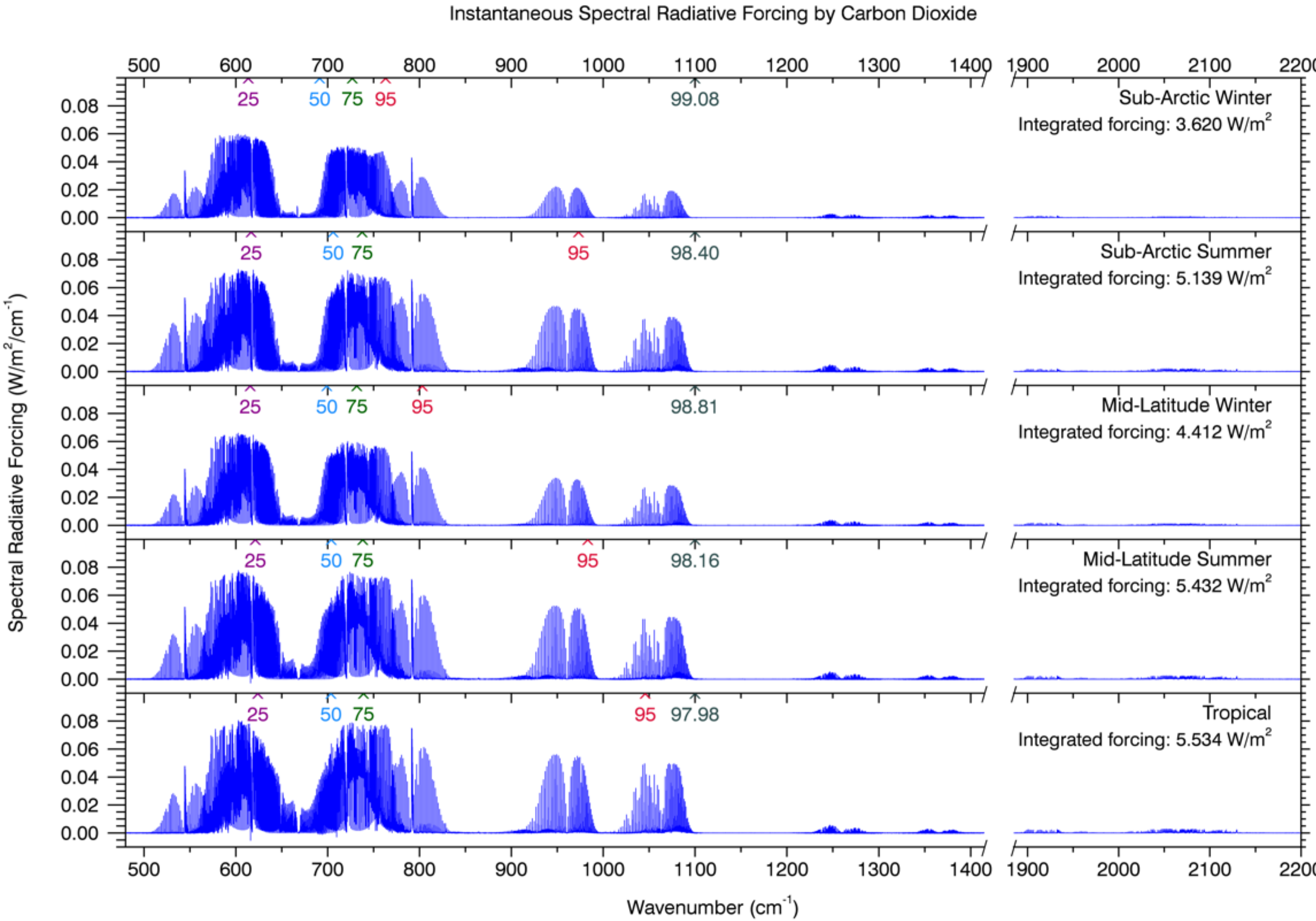
Status

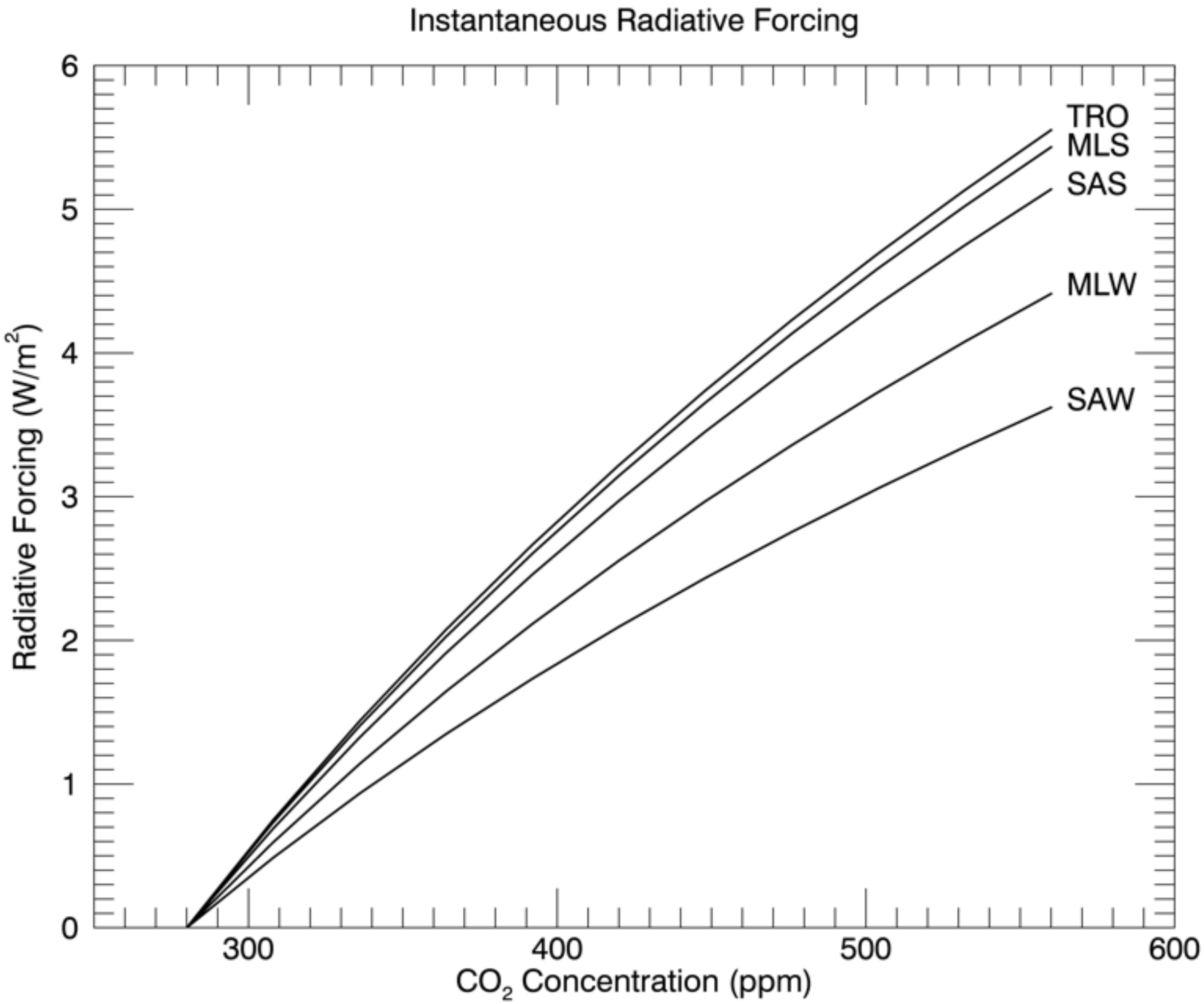
- Our team has been working to investigate the uncertainty in radiative forcing due to spectroscopy
  - Line strengths; Air-broadened half widths; Line shape function
- We find that there is very small uncertainty in the computation of radiative forcing (RF)
  - Largely due to the definition of RF – a double difference in which correlated errors cancel almost exactly
  - Validated this with full error analysis
- RF is change in net flux at tropopause from pre-industrial times to time "t", usually present day or doubled CO_2
- We examine in particular RF for doubled CO_2
- $RF = F_{net}(2 \times CO_2) - F_{net}(CO_2)$ at tropopause
- $Fnet = F_{down} - F_{up}$

<u>The RF calculations are robust with uncertainty less than 1%</u>

The Spectrum of CO_2 Radiative Forcing - LBLRTM

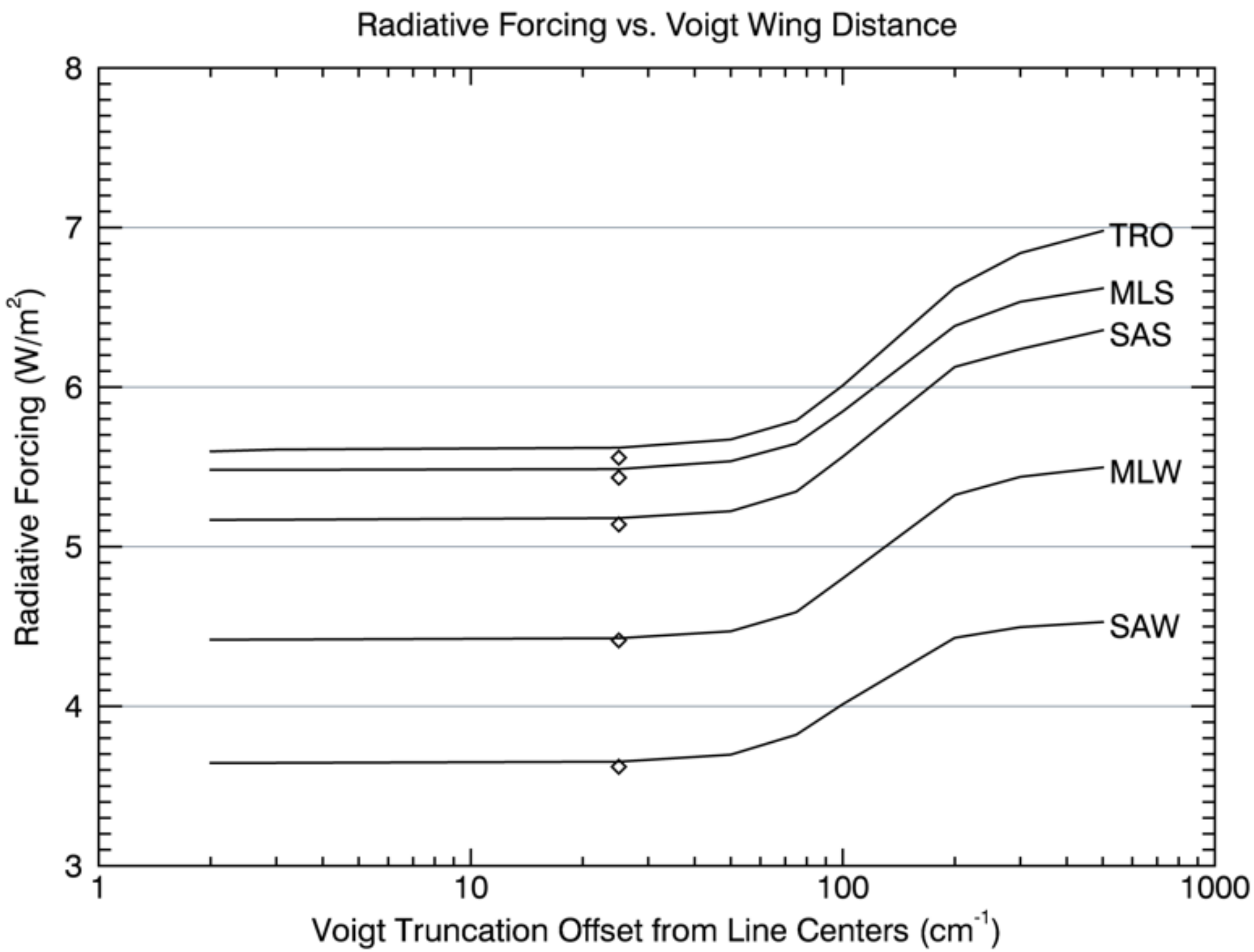


Instantaneous Radiative Forcing by CO_2

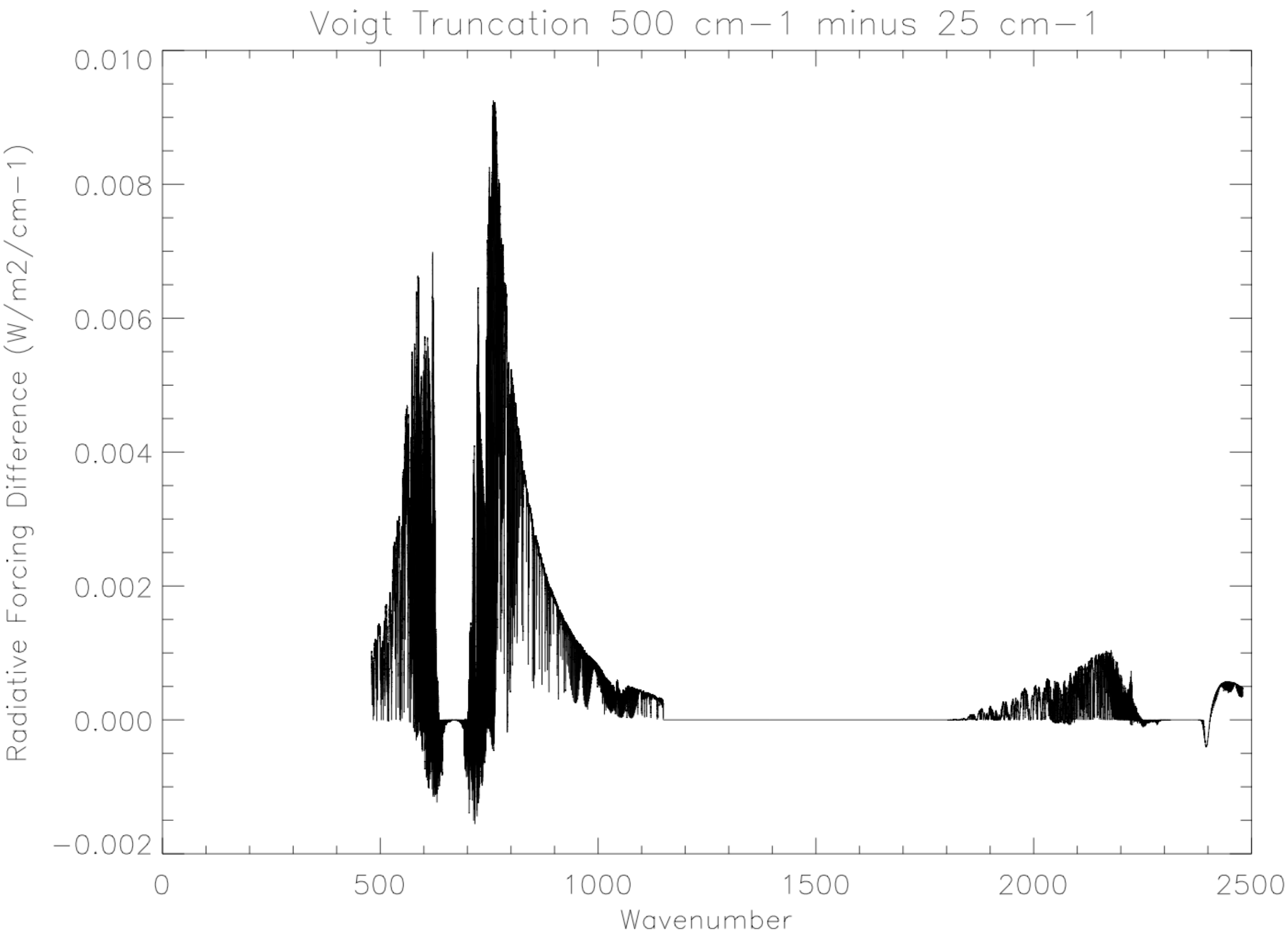


Note ~ logarithmic growth of forcing with CO_2 concentration

Effect of Voigt Wing Extent on RF

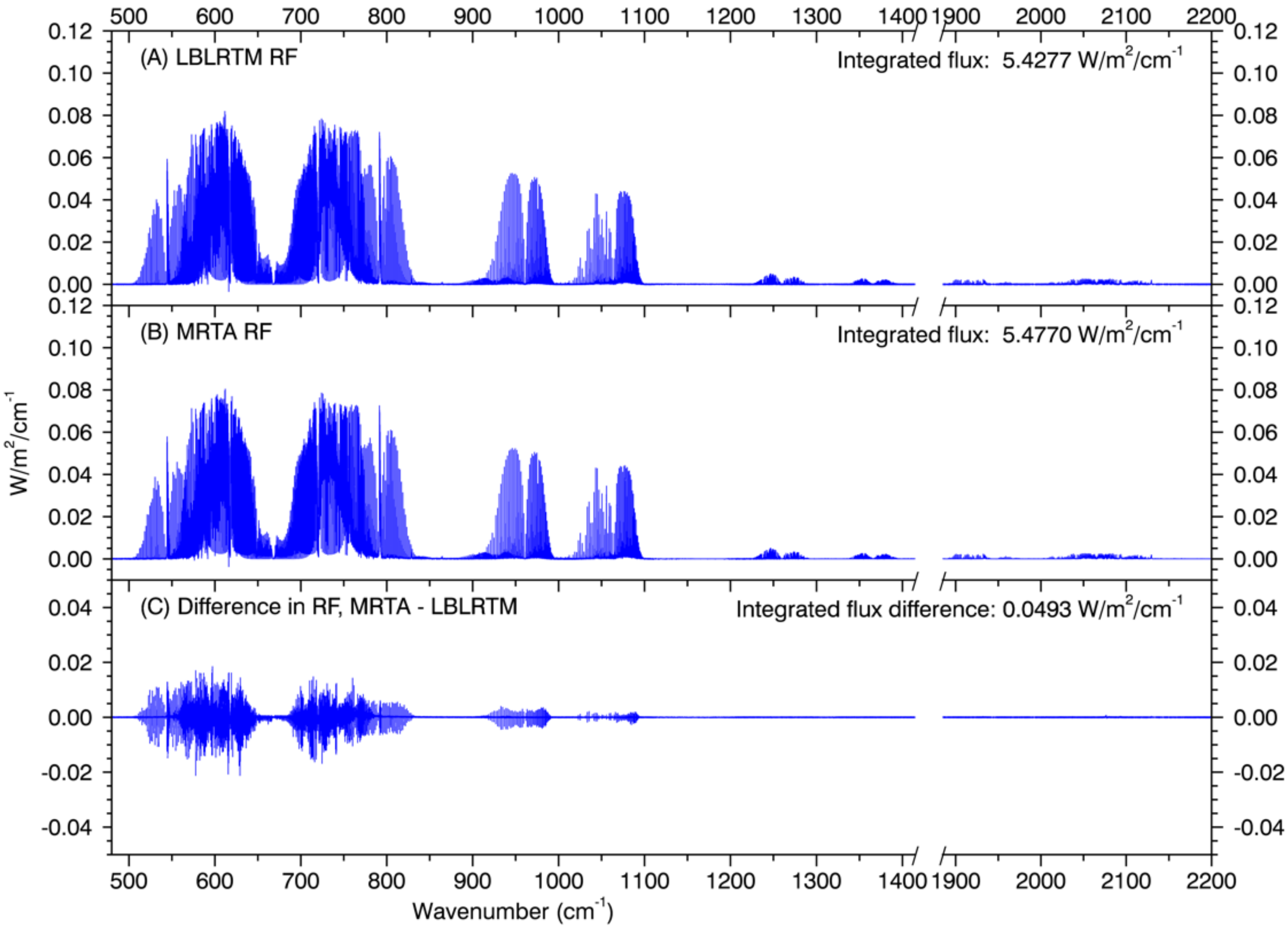


Radiative Forcing Difference
Voigt shape truncated 500 cm^{-1} minus truncation at 25 cm^{-1}



Effect of Sub-Lorentzian Wings on RF

LBLRTM - MRTA

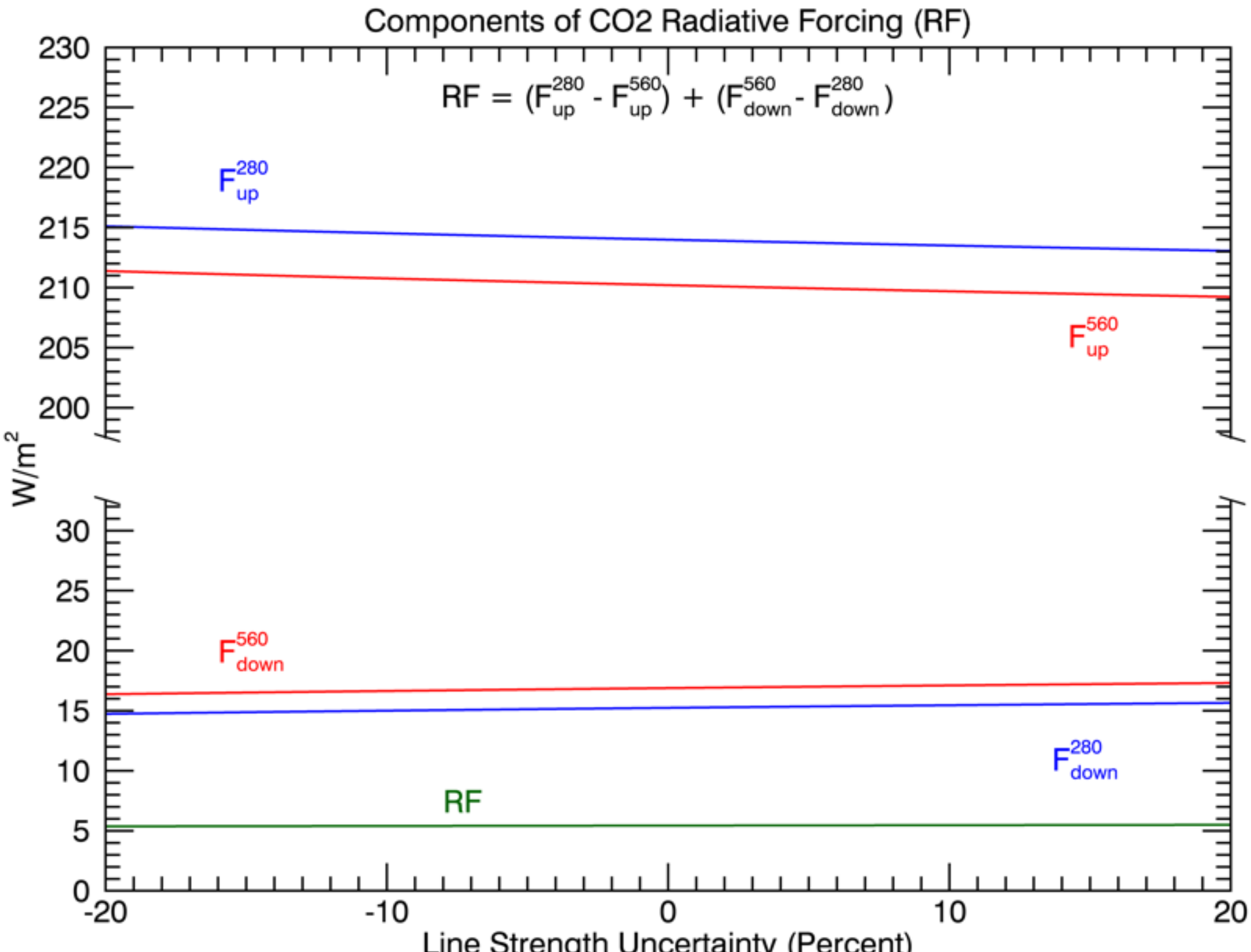


(Lack of) Sensitivity of RF to Line Strength, Halfwidths

- Uncertainties in spectroscopy impact the computation of atmospheric transmittance, and potentially, the computed RF
- Approach:
  - Compute RF by varying strengths of ALL lines of CO_2 from -20% to +20% in steps of 1%
  - Illustrate correlated nature of uncertainty
  - Compute RF using uncertainties specified in AER line database
  - Use full error analysis including correlated and uncorrelated error terms
- Results:
  - Small (< 1%) uncertainties in RF due to correlated nature of errors

Sensitivity of RF to Uncertainty in Line Strengths

(Sensitivity to halfwidths behaves similarly)



Accounting for Correlated Errors
Standard Approach using Covariance

$$\sigma_F^2 = \sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 \sigma^2(x_i) \quad + \quad 2\sum_{j=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}\sigma(x_i, x_j)$$

This is the standard law of propagation of error defined in the NIST "GUM", the Guidelines for Uncertainty Measurement, NIST TN 1297

The x_i are the up and down fluxes, f is the forcing.

The $\sigma^2(x_i)$ are the uncertainties associated with the up and down fluxes

The $\sigma(x_i, x_j)$ are the covariance associated with the up and down fluxes
(6 covariance terms in all since 4 fluxes)

Summary of Uncertainties in RF due to Spectroscopy

Table 2. Uncertianties (W/m^2) in radiative forcing due to uncertainty in line strength, collision broadened halfwidths, and spectral lineshape. RSS is the root-sum-square of the three error terms. The last column is the RSS expressed as a percentage of the corresponding RF in Table 1 above.

Atmosphere	Line Strength W/m^2	Half Width W/m^2	Line Shape W/m^2	RSS W/m^2	% Baseline Forcing
MLS	0.0146	0.0057	-0.0121	0.0198	0.37
MLW	0.0111	0.0089	-0.0186	0.0234	0.53
SAS	0.0157	0.0091	-0.0162	0.0243	0.47
SAW	0.0094	0.0076	-0.0226	0.0256	0.71
TRO	0.0140	0.0034	-0.0006	0.0144	0.26

These values will be updated in the GRL paper

Halfwidth errors are even less than shown due to improved accuracy of collision broadened parameters (Gamache and Lamouroux, 2013)

Conclusions and Next Steps

- Uncertainties in spectroscopic parameters (line strengths, halfwidths, line shape) contribute in total < 1% error to computed radiative forcing
- Journal article is ready to submit – going to GRL as likely fastest route to publication online after acceptance
- Talks at Fall AGU, submitted to International Radiation Symposium
- Circulate accepted paper and results far and wide

Backups

Fluxes and Radiative Forcing vs Voigt Wing Extent